

Offset Stream Technology Test—Summary of Results

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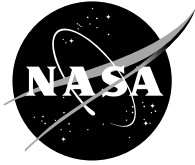
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Abstract

The concepts studied during Offset Stream Technology (OST) test were all designed to produce directional jet noise reduction in a separate flow engine configuration by redirecting the fan stream relative to the core stream, creating a thicker fan flow on one side of the jet. Previous studies, conducted at bypass ratios of five or less showed that lower noise levels would result on the thickened side. The OST test, conducted using nozzles with bypass ratios 5, 8, and 13, included flow and acoustic measurements over a wide range of engine bypass ratios, jet conditions, and flight speeds for three offset stream concepts: wedges, vanes, and an S-duct. Mean axial velocity data, measured in cross-stream planes showed that all these concepts successfully created the fan stream offset as intended. Additionally, far field acoustic measurements showed that the vanes and S-duct reduced the noise on the side of the jet with the thicker fan stream below the levels measured from the concentric baseline jet. However, adding a flight stream, to simulate Mach 0.2 forward flight, diminished the effectiveness of offset stream devices, reducing or completely eliminating most of the noise benefits. Furthermore, while engine condition (i.e., takeoff and cutback) did not have a large impact on the noise, engine bypass ratio had a significant impact on the effectiveness of the offset stream concepts. The offset stream devices had much less impact on the jet noise at higher bypass ratios than in lower bypass ratio configurations. In fact, only modest reductions were noted from the best bypass ratio 8 configuration. Above bypass ratio 8, the results from the offset jet were very similar to the baseline. Future work should, therefore, be directed at lower bypass ratio applications.

I. Introduction

The concepts tested during the OST test were all designed to reduce the impact of the jet noise generated by a separate flow engine by using the engine geometry itself to alter the directionality of the sound produced. Each concept, using a different method, attempts to modify the fan stream to favorably modify the propagation of sound generated by the fan-core shear layer on one side of the jet. Any reduction on the thickened fan stream side seem to come at the expense of increased noise on the opposite side of the jet. In practice, the louder side of the jet would be directed away from the ground to take full advantage of the directionality of the noise reduction. It should be noted here that the term ‘shielding’ is used here but the underlying mechanism is not be the same as that associated with thermal layers where redirection of noise occurs through refraction.

While there could be many methods that would create the offset stream effect leading to the directional noise reduction, only three were selected for the OST test program. The first method employed an S-bend in the fan duct upstream of the fan nozzle. The S-duct allows the offset to be created inside the engine by shifting the nozzle laterally and, therefore, allows the fan and core streams to remain parallel at the nozzle exit planes. The second device, a wedge at the fan nozzle exit, creates the thickened fan stream by driving the flow around the annulus away from the wedge. Three different wedges were tested during

the OST program. The third concept investigated was the fan vane. These small airfoils redirect the fan flow to one side, forming the thicker fan stream. Unlike the S-duct, the fan vanes and the wedges, by design, create two nonparallel streams. Data from many vane configurations were recorded as part of an MDOE study during the OST tests. Each of these three concepts has its own advantages and disadvantages when deployed in a real engine application. The OST test program was designed to evaluate each concept for acoustic performance on a medium scale test rig at real engine cycle conditions.

In the OST test program each concept was evaluated for far field noise levels on both the thickened and thinned fan stream sides of the jet. Additionally, diagnostic measurements, in the form of acoustic phased array and PIV, were deployed to provide insight into the physics of noise production in these offset stream designs, to validate the prediction codes used during the concept development phase, and to serve as a base for the next generation of flow offset devices. Both the acoustic and flow data collected were used to compare with and validate data previously obtained at small scale jet facilities with simulated heat effects (ref. 1).

A. History

The origin of the OST test dates back to earlier studies in 2001 when researchers at the University of California, Irvine (UCI), led by Papamoschou, observed directional noise reduction in separate flow supersonic jet when an S-duct was used to offset the core stream relative to the fan flow (ref. 2). They concluded that the eccentric arrangement reduced Mach wave radiation on the bottom of the jet (with the thicker fan stream) and enhanced mixing, reducing the length of the potential core resulting in reduced noise on that side. These results were confirmed at NASA Glenn Research Center (GRC) by Zaman in 2004 (ref. 3). Also in 2004, new work conducted at UCI found that noise reduction could be achieved by using guide vanes to tilt the fan stream relative to the core stream (ref. 4). This work, and the follow-up in 2005 (ref. 5), extended the offset stream concept from supersonic jets to subsonic jets. In 2006, the effect of a wedge in the fan stream for creating a flow offset was studied at UCI and NASA GRC for directional noise reduction (ref. 6). The results from both facilities showed that the impact of the wedge on the jet noise is very dependent on the nozzle flow lines. Additional vane and wedge refinements have continued at UCI in search for greater noise reduction (ref. 7).

The OST program is the culmination of the ideas developed at the UCI and tested at a moderate scale facility at NASA GRC. These concepts, which originated on supersonic jet flow conditions at low engine bypass ratios (BPR), were extended down to subsonic jets at higher bypass ratio (BPR 5, 8, and 13) for the OST tests. Computational fluid dynamics (CFD) were used early in the program to screen parameters for the wedge and vane design. These results, which would later be evaluated against the test flow data, led to the particular wedge and vane devices tested (ref. 8). Also, for the fan vanes, a MDOE matrix was developed to identify the optimal vane design for the BPR 8 model (ref. 9). Once the planning and CFD was complete, the testing began with far field and phased array acoustics (acquired simultaneously) and was followed by PIV flow measurements. This paper will examine the flow and far field acoustic results for the wedge and S-duct configurations as well as select vane cases.

II. Experimental Facility and Data Acquisition

A. Jet Rig

The High Flow Jet Exit Rig (HFJER) located in the AeroAcoustic Propulsion Laboratory (AAPL) at the NASA Glenn Research Center in Cleveland, Ohio (fig. 1) was used for the OST test program. The HFJER is capable of both internally mixed and separate flow configurations using air supplied at 450 psi from a remote compressor. Heat is added to the core stream using a natural gas combustor. The rig is capable of mass flow rates up to 20 lbm/s at jet exit temperatures up to 1425 °F. The HFJER is located inside the Nozzle Acoustic Test Rig (NATR), a 53 in. diameter freejet that provides a simulated flight stream at speeds up to Mach 0.3. The AAPL, a geodesic dome with a radius of 65 ft, is lined with sound



Figure 1.—The High Flow Jet Exit Rig (HFJER) mounted in the Nozzle Acoustic Test Rig (NATR) at the AeroAcoustic Propulsion Laboratory at the NASA Glenn Research Center in Cleveland, Ohio.

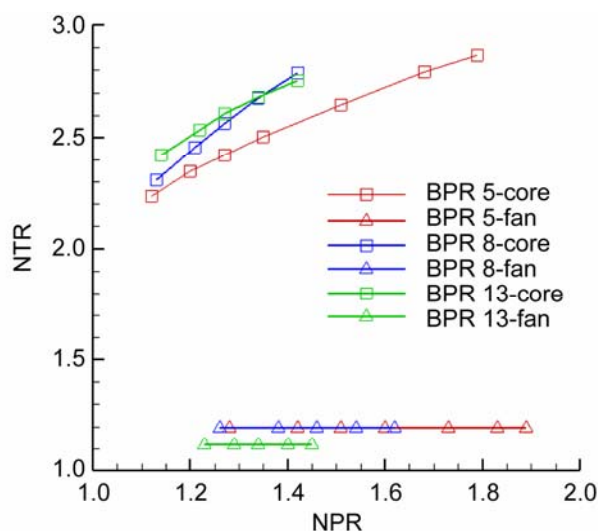
absorbing wedges to create an anechoic environment at frequency above 200 Hz. Ambient temperature, pressure, and humidity and all jet conditions are recorded by the facility ESCORT computer. More detail on the AAPL and NATR can be found in reference 10.

Jet exit conditions were defined using core nozzle pressure ratio (NPR_c), fan nozzle pressure ratio, (NPR_f), core nozzle temperature ratio (NTR_c), fan nozzle temperature ratio (NTR_f), and flight Mach number (M_{ff}). Each combination of defined values was assigned a “setpoint” number code and input into the ESCORT facility computer. ESCORT then provided a real time error, updated once per second using an average of all setpoint variables, to ensure the data acquired was at the desired jet condition. For the data to be accepted, the total error between the defined setpoint value and the actual measured value when averaged over all setpoint variables had to remain below 0.5 percent for the entire record time. Figure 2 shows the jet exit conditions and setpoint number codes for the data presented in this paper.

The HFJER was modified before the OST test program to improve data quality, particularly at the upstream angles. A series of choke plates and reticulated foam metal (RFM) were altered in the fan duct upstream of the charging station to maximize the pressure drop inside the rig itself. This lowered the flow velocity in the supply piping which decreased the noise created by the flow passing through the pipe elbows and baffles. An unintended side effect, however, is the noise created by the RFM inside the rig that propagates past the nozzle exit and appears in the far field data at frequencies above 20 kHz. The data were vetted using a model of the rig noise at each angle and subtracting it from the data, generally leaving a useful frequency range up to 30 kHz. Thus, the spectra presented here will be cut off at 30 kHz.

B. Acoustic Measurements

Far field acoustic data were measured using an array of 24 Bruel and Kjaer type 4939 1/4 in. microphones placed at 5° intervals on a track above the jet. Bruel and Kjaer Nexus amplifiers provided signal conditioning and amplification. The data were digitized, at a 200 kHz sample rate with a 90 kHz low pass filter, using a DataMAX Instrumentation Recorder from R.C. Electronics. Once acquired, data were transformed to narrowband spectra (using a 2^{14} point window for a bin width of 12.21 Hz) and background noise was subtracted. The data were then corrected for microphone response, using the



Setpoint	BPR	NPR_c	NTR_c	NPR_f	NTR_f	M_{fj}
0210/2	5	1.680	2.793	1.830	1.192	0.0/0.2
0030/2	8	1.270	2.562	1.460	1.192	0.0/0.2
0050/2	8	1.420	2.790	1.620	1.192	0.0/0.2
0710/2	13	1.340	2.682	1.400	1.117	0.0/0.2

Figure 2.—All jet conditions tested during the OST program plotted as NPR versus NTR for the core and fan streams. All bypass ratios are included. Selected jet conditions, included in this paper, are defined in the table with their associated setpoint code.

calibration supplied by Bruel and Kjaer, and for refraction at the freejet shear layer before being converted to a one-foot lossless condition. The data could then be transformed to a full-scale flyover scenario using a scale factor of 8 and a 1500 ft. flight altitude at standard day conditions. A Mach 0.28 flight speed was assumed for all EPNL calculations.

One extra data processing step was required for the data acquired from the jets offset by vanes. Because the hardware was designed to allow for interchangeable configurations, each vane was attached to the core cowl using screws. The screw heads, however, created a tone in the far field data at a frequency that varied with flow velocity. While the tone could be removed by covering the screw heads with Ni-Chrome strips, the process was considered too time consuming for the number of model changes planned and, because of the predictable nature of the tones, the tones could be removed during post processing by using linear interpolation across the narrowbands affected by the tone. The difference between a case where the screw heads were covered and the identical case where the tone was removed during post processing was less than 0.1 dB in the third octave band of the tone.

C. Flow Measurements

Flow data were acquired using Stereoscopic PIV, in the cross-stream plane, at 6 axial locations. All three components of jet velocity (u , v , w) were determined using this technique. The core and bypass flow was seeded using atomized alumina particles ($\sim 0.5 \mu\text{m}$ diameter) and the ambient or flight stream was seeded using a commercial fog generator. A lightsheet was supplied by a dual-head Nd:YAG laser. Two cross-correlation cameras, placed at an angle of 40° relative to the flow, were used to acquire 200 image pairs. These were processed, using software developed at NASA, to calculate 200 instantaneous velocity vector maps at each location (ref. 11). These velocity maps were then used to calculate mean velocities and turbulence statistics.

The PIV data recorded during the OST test was afflicted with a couple of problems not observed in either previous or more recent PIV experiments. First, the ambient seed was not consistent in particle size or density leading to some unrealistic vector results in the flight stream near the nozzle and in the fully mixed jet. The second problem, which is again related to the ambient seeding, was particular to the wedge configurations. Because there is no fan flow behind the wedge, the ambient flow must seed that region. The ambient flow, however, did not immediately fill the space behind the wedge during image acquisition, leaving poor quality data in the first cross-stream plane. Additionally, model reflection was an issue in the data recorded at the first plane.

III. Offset Flow Hardware

A. Wedges

A wedge, placed at the exit of the fan stream with the base near the fan nozzle exit (fig. 3), creates a significant blockage on one side of the fan stream forcing the flow to the opposite side of the jet. The four wedges used during the OST test program were designed to study the effect of wedge angle and base length, at two engine bypass ratios, as variables for creating the directional noise reduction desired. The first wedge, with an 11° half angle and 3.4 in. base (BPR5-W1), was built to replicate the parameters of the wedge previously tested at UCI using the BPR 5 engine cycle. A second wedge (BPR8-W1), using the same angle and base length, was built for the BPR 8 configuration to investigate the offset stream effect at a higher engine bypass ratio. Both flow and acoustic data were acquired for these wedges. Two additional wedges were tested on the BPR 8 configuration. The first of these (BPR8-W2) had a 20° half angle but retained the 3.4 in. base length, a wedge that is shorter in the axial direction. The final wedge (BPR8-W3) reduced the base length to 2.4 in. but kept the 20° half angle of the BPR8-W2 wedge to create the shortest wedge with the smallest blockage area tested. Only acoustic data were recorded for wedges BPR8-W2 and BPR8-W3. Critical dimensions for all wedges, with a schematic of a wedge, are shown in figure 4. No wedges were tested with the BPR 13 model system.

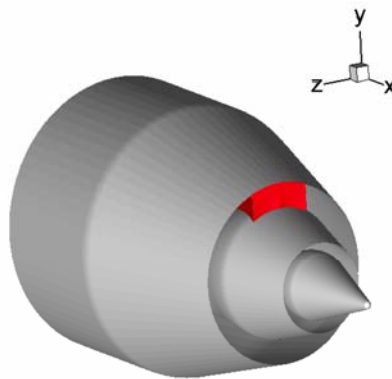


Figure 3.—A wedge is installed at the exit of the fan duct. The wedge serves to force the flow to the opposite side of the jet creating the offset fan and core streams.

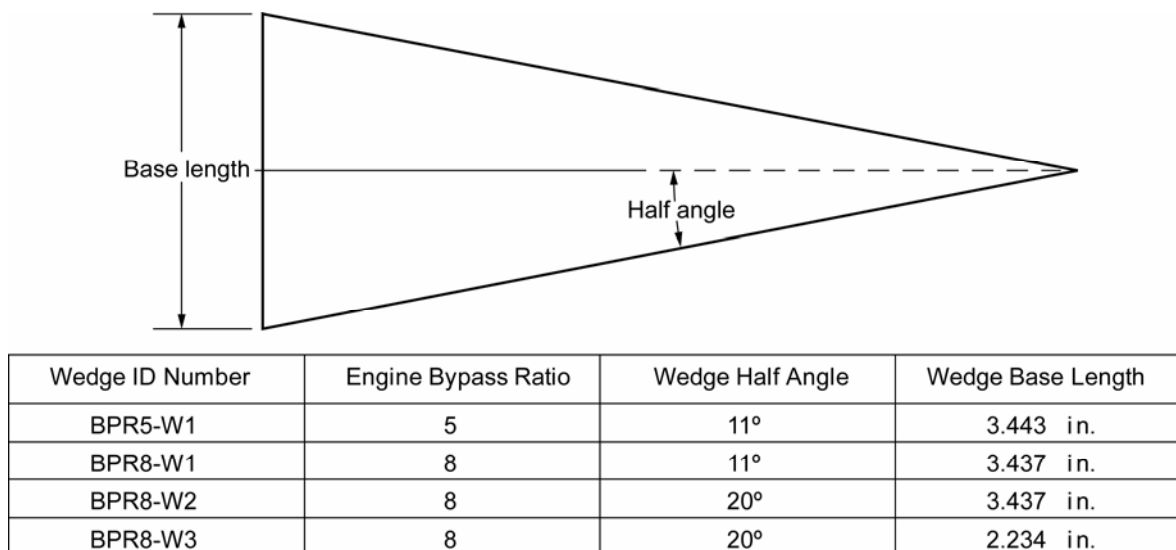


Figure 4.—Dimensions of all wedges tested during the OST05 program.

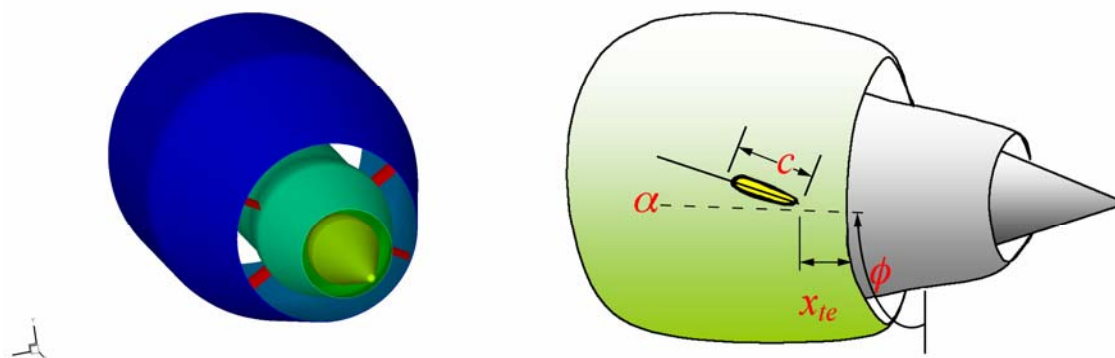


Figure 5.—A drawing showing how the vanes were installed in the model (left) and a drawing showing the parameters considered during the OST test (right) where α is the vane angle of attack, ϕ is the azimuthal angle of the vane location, X_{te} is the axial distance from the end of the vane to the fan exit plane, and c is the vane chord length. Note that the parameter actually for axial location was the normalized value X_{te}/c .

B. Vanes

Airfoil shaped turning vanes were also used to create the offset streams and, therefore, the desired directional noise reduction (fig. 5). The flow vanes tested during the OST program had several parameters that were manipulated to determine the optimal amount of offset (fig. 5). First, the vane angle of attack (α) is the most direct method of adjusting the offset between the fan and core streams. Second, the azimuthal location of the vanes (ϕ) changes the direction and amount of offset and, thus, the direction and magnitude of the noise reduction. Finally, the axial location of the vanes, normalized by the vane chord length (X_{te}/c), was explored. One goal was to determine how far upstream the vanes could be mounted and still achieve the desired noise reduction benefit. Because each combination of variables required its own static hardware, the number of configurations tested was limited. A core cowl piece was built to mount different combinations of vanes and blanks maximizing the number of configurations while minimizing the fabrication expense. A subset of the total vane configurations tested is shown in table 1.

TABLE 1.—VANE CONFIGURATIONS BEING REPORTED. REFER TO FIGURE 4 FOR DEFINITION OF PARAMETERS.

Configuration	BPR	α_1 (°)	α_2 (°)	x_1/c_1	x_2/c_2	ϕ_1 (°)	ϕ_2 (°)
BPR5-V1	5	15	10	0.5	0.5	70	110
BPR8-V1	8	7.5	7.5	0.5	0.5	60	120
BPR8-V2	8	5	5	0.75	0.75	50	130
BPR8-V3	8	5	5	0.25	0.25	50	130
BPR8-V4	8	10	10	0.75	0.25	50	130
BPR8-V5	8	10	10	0.25	0.25	50	130
BPR13-V1	13	5	5	0.75	0.25	50	130

C. S-Duct

Perhaps the simplest offset stream device in concept tested during the OST test, the S-duct creates the offset between the fan and core streams upstream of the fan nozzle exit plane (fig. 6). The S-duct, by design, retains parallel streams at the nozzle exit and minimizes flow blockage while creating a very controlled offset. For the OST test, one S-duct was fabricated and used on the BPR 5, 8, and 13 model systems.

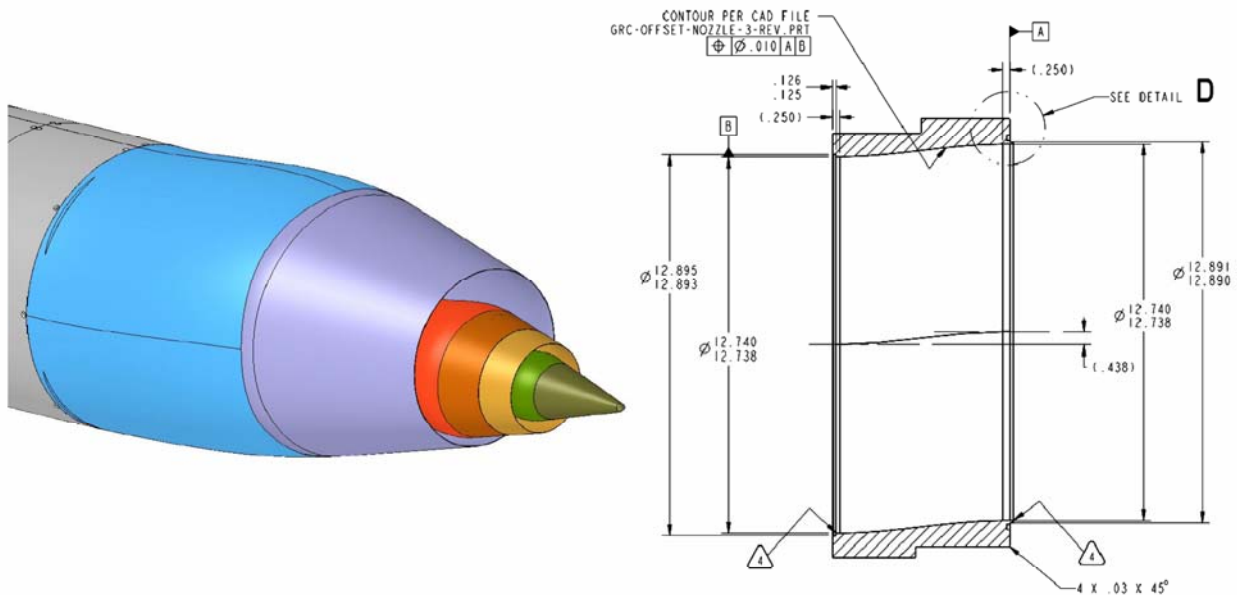


Figure 6.—S-duct installed in the jet rig (right) and schematic of S-duct part (left) used to create a 0.438 in. offset in the fan stream relative to the core stream. Only one S-duct was build for the OST test. It was used on the BPR 5, 8, and 13 model systems.

IV. Results

A. Flow and Turbulence Measurements

PIV was used during the OST test program to assess the performance of each offset stream in creating the thicker fan stream for directional noise reduction. In addition, turbulent kinetic energy (TKE) ($TKE = 0.5(u^2 + v^2 + w^2)$), a primary component in determining the amount of jet noise, was calculated from the PIV velocity data. PIV data was recorded at six cross-stream planes ranging from 1 fan diameter (D_f) to $7 D_f$ downstream of the fan stream exit plane where $1 D_f$ is very near the plug tip. Figure 7 shows the mean axial velocity at five cross-stream planes for the BPR 8 baseline, BPR8-V5 vane, BPR8-W1 wedge, and BPR8 S-Duct cases. These velocity profiles clearly show that each device generates the thicker fan stream required for directional noise reduction. The different methods used to reach this result, however, show up in the shape of the axial velocity profiles. The BPR8-V5 vane configuration, for example, creates a fan flow that is almost rectangular in shape on the shielded side while leaving some fan flow on opposite side with a much flatter profile compared to the round baseline. By contrast, the BPR8-W1 wedge leaves the thickened fan stream side with a round profile but nearly cuts off the fan flow to the opposite side, a result that could be anticipated based on the wedge design alone. The velocity profile from the S-duct shows that the fan stream has been shifted relative to the core stream but the plume shape is not significantly changed near the nozzle exit. This result could also be easily predicted from the S-duct concept. The first goal of each offset stream concept, shifting the fan stream relative to the core stream to enhance the fan flow on one side of the jet, is accomplished by all three technologies tested.

The vanes, wedges, and S-duct all succeed in creating an offset plume as illustrated by the mean axial velocity profile. This data also shows that the axial velocity decays faster in all of the offset jets than in the concentric baseline jet where at least some of the high speed core is still present at $x/D_f = 7$. The velocity decay is most rapid in the vane (BPR8-V5) and wedge (BPR8-W1) data where the high velocity core region is not present by $x/D_f = 5$. The velocity decay is less pronounced in the S-duct data, where the highest velocities are still present at $x/D_f = 5$ but not at $x/D_f = 7$. Figure 8 shows the peak axial velocity, as a function of axial position, for the BPR 8 baseline, vane, wedge, and S-duct configurations for jet condition 0052 (fig. 2). The peak axial velocity is nearly independent of configuration in the first $x/D_f = 2$ downstream of the fan nozzle exit plane. At that point, the axial velocity in the jet with the wedge, the most aggressive configuration, quickly decays below all the other configurations. The S-duct, with a very thin shear layer on one side, and the BPR8-V5, representing the most aggressive vane settings with a 10° angle of attack near the nozzle exit, also cause the axial velocity to decrease below the baseline at axial points beyond $x/D_f = 2$. The BPR8-V2 and BPR8-V4 velocity profiles follow the baseline values farther downstream. The BPR8-V4 vane settings cause the peak axial velocity to decay below the baseline at $x/D_f = 3$ but it does not go as low or as quickly as the BPR8-V5 configuration. This is interesting because both have a 10° angle of attack but the BPR8-V4 vanes move one set of vanes upstream by $x_1/c_1 = 0.5$ compared to the BPR8-V5 vanes. Moving the vanes upstream, therefore, appears to decrease their effectiveness at altering the jet plume. The BPR8-V2 vanes, which show peak axial velocities similar to the baseline, are the most conservative, using a 5° angle of attack. Each configuration creates an offset jet using a different approach and, judging by peak axial velocity decay, the wedge was the most extreme offset stream device tested. The S-duct was also shown to be quite aggressive, while the vanes appear quite flexible depending on several parameters. As might be expected from the vane concept, increasing the angle of attack and moving the vanes closer to the nozzle exit increased the impact they had on the jet. Although studying velocity profiles does give some insight into how each device changes the jet, differences in the noise produced was more related to the changes in turbulent kinetic energy than mean velocity profile.

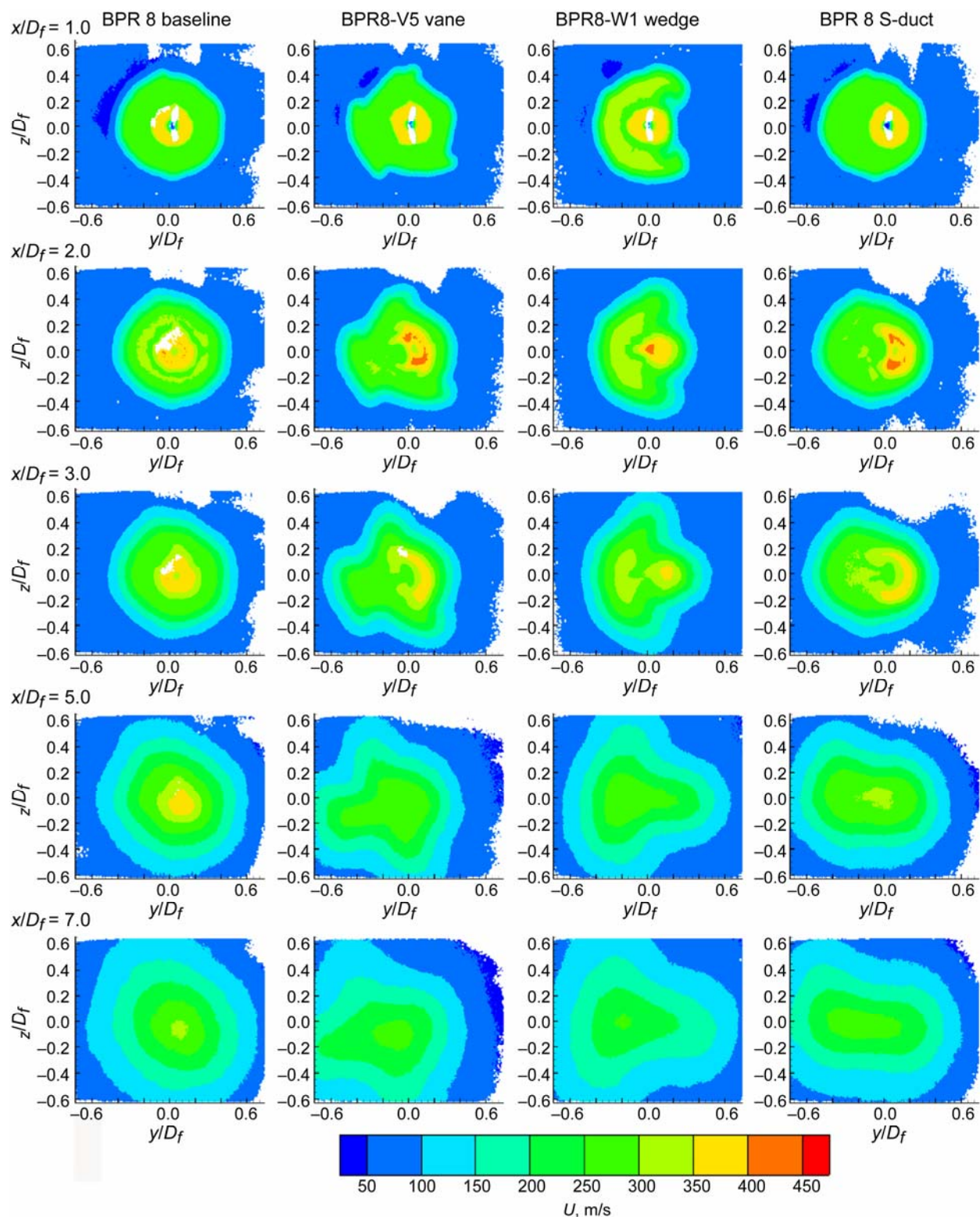


Figure 7.—Average axial velocity for the BPR 8 baseline, BPR8-V5 vane, BPR8-W1 wedge, and BPR 8 S-duct configurations at 5 axial planes from $x/D_f = 1.0$ to $x/D_f = 7.0$ for jet condition 0052 (fig. 2). Note that x/D_f is very near the plug tip causing some data near the centerline to be lost to model reflection. Also, some data near the edges of the frame was lost due to problems with the ambient seeding. Data below a quality of 0.25 has been removed from each plot.

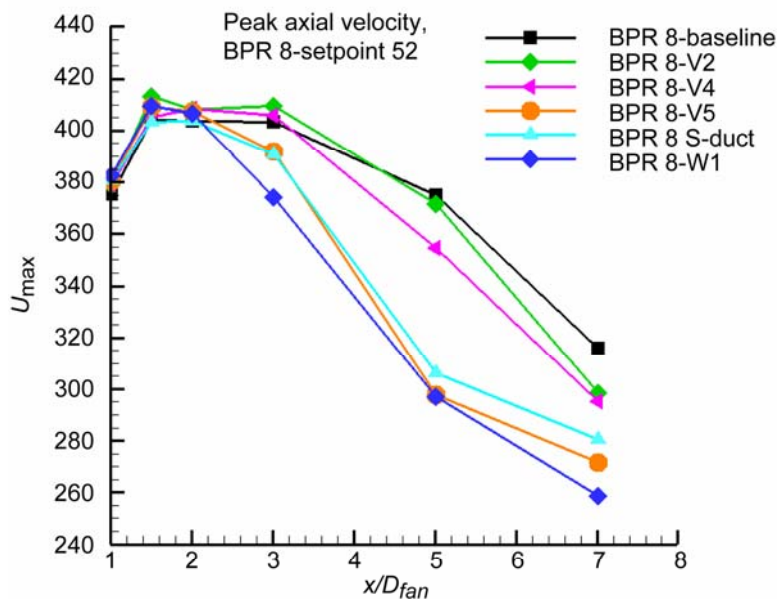


Figure 8.—Peak axial velocity for the BPR 8 vane S-duct and wedge configurations at 6 planes from $1D_{fan}$ to $7D_{fan}$ for jet condition 0052 (fig. 2). Peak velocity was defined as the maximum value anywhere in the frame except at the first axial station where the peak point was also required to be outside of the area affected by model reflection.

The turbulent kinetic energy was calculated from PIV velocity maps to understand how these offset stream jets might be designed for optimal noise reduction benefit. In general, it was expected that the TKE would increase, perhaps dramatically, on the side with the thinner fan stream while remaining unchanged or slightly decreasing on the thickened side of the jet. Figure 9 shows the TKE, normalized by the fan velocity squared (V_{fan}^2), for the BPR 8 baseline, S-duct, BPR8-W1 wedge, and BPR8-V5 vane configurations at jet condition 0052 (fig. 2). Other than changes in the shape of the fan stream shear layer, there was little change in the TKE in the first 2 fan diameters of the jet with the exception of the BPR8-W1 configuration. Because the wedge effectively blocks the fan flow entirely on that side of the jet, the very high levels of TKE immediately downstream of the nozzle exit on the wedge side are created by the interaction between the core flow and the ambient. If normalized by the core velocity (V_c) squared, the normalized values fall in line with the other configurations. At $x/D_f = 3$ the vane and, particularly, the S-duct data have an increase in TKE on the side of the jet with the thin fan stream. For the S-duct, this appears to be where some of the core flow reaches the ambient through the smaller fan stream. By $x/D_f = 5$ the TKE is starting to decrease on the wedge side of the BPR8-W1 jet while it continues to increase in the vane and S-duct jets. Also at $x/D_f = 5$ the fan shear layer on the thickened side of the jet continues expanding, a trend that persists through $x/D_f = 7$.

The growth and decay of TKE for all the BPR 8 configurations is compared in figure 10 where the peak TKE is plotted as a function of axial position for both the entire jet and for the thickened fan stream side only. The peak TKE follows the general trend, in terms of growth and decay of TKE, observed in cross-stream TKE profiles (fig. 9). The peak TKE also follows the growth and decay trend observed in the analysis of axial velocity. The highest TKE is observed in the BPR8-W1 wedge jet, identified as the most aggressive design based on the decay of the mean axial velocity. Also, TKE data from the S-duct and BPR8-V5 vane cases deviated significantly from the baseline configuration with higher levels near the nozzle exit and more rapid decay rate at downstream locations. Finally, the BPR8-V2 and BPR8-V4 configurations were most similar to the baseline. The data in figure 10 also shows that the thicker fan

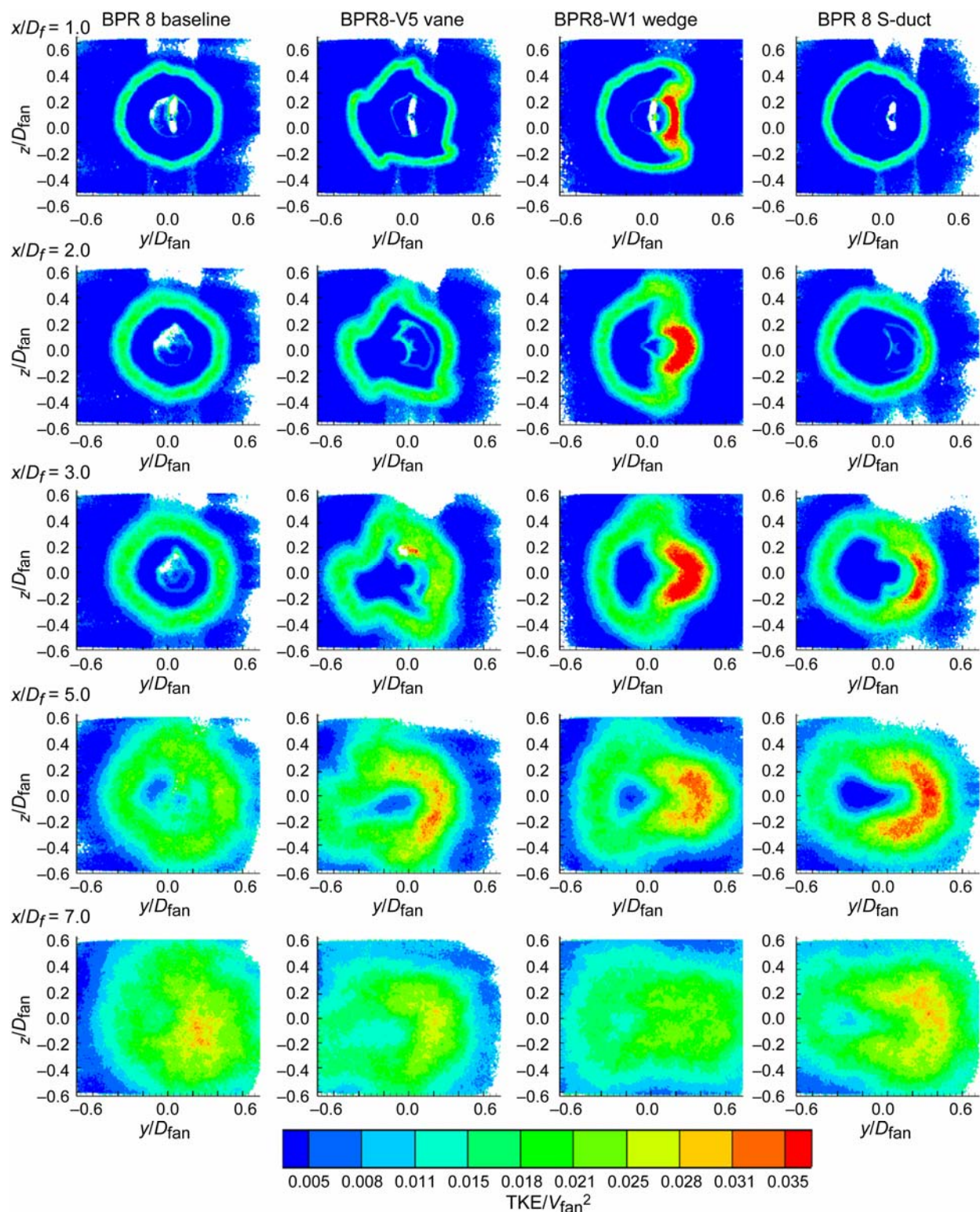


Figure 9.—Turbulent kinetic energy (TKE), normalized by fan velocity squared (V_{fan}^2) for the BPR 8 baseline, BPR8-V5 vane, BPR8-W1 wedge, and BPR 8 S-duct configurations for jet condition SP0052 (fig. 2). As expected, the TKE is significantly higher on the side with the thinner fan stream. The high TKE points (above 0.035) show where there is interaction between the core stream and ambient and where the data may be better normalized by the core velocity.

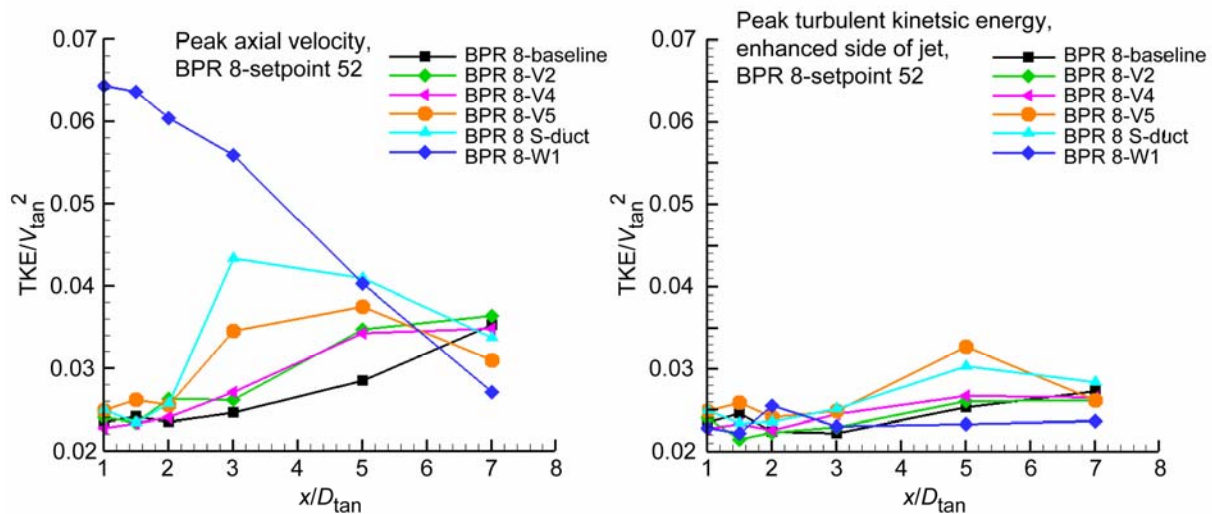


Figure 10.—Peak turbulent kinetic energy (TKE) for the BPR 8 baseline, vane, wedge, and S-duct cases recorded at jet condition SP0052 (fig. 2). The first plot (left) shows the peak TKE measured at any location in the jet while the second plot (right) shows the peak TKE measured only on the side of the jet with the thicker fan stream.

stream has little impact on the peak TKE on that side of the jet when compared to the baseline data. Thus, if peak TKE is the primary predictor of noise produced, the thicker fan must act as a significant noise shield. Otherwise the high peak TKE levels measured on the thin side of the jet indicate that more noise will be created while the TKE values on the thicker side of the jet predict noise levels similar to the baseline jet. The offset jet would then generate more total noise than the baseline and, without significant propagation benefit from the thicker fan stream, any noise benefit compared to the baseline jet would be lost.

B. Acoustic Measurements

The wedges, vanes, and S-duct configurations tested during the OST test program all created a thicker fan stream, on one side of the jet, to achieve noise reduction on that side of the jet. To determine the amount of directional noise reduction far-field acoustic data were taken from an extensive list of configurations at bypass ratios 5, 8, and 13 and jet exit conditions from takeoff to approach. Data was recorded in a static environment and with a Mach 0.2 flight effect.

1. Wedges

The flow measurements showed that the wedge was the most aggressive offset flow design tested. Particularly, the TKE was exceptionally high on the wedge (or thin fan stream) side of the jet. Figure 11 shows 1/3-octave spectra for all the BPR 8 wedge configurations at the 0050 jet condition. All the wedges have a significant increase in noise at the 90° observer location on both sides of the jet with the BPR8-W1 wedge performing the best acoustically. Conversely, the BPR8-W2 wedge is the worst with the thicker fan stream side almost at the same level as the thinner fan stream side. The spectral peak is shifted to higher frequencies relative to the baseline in all the wedge cases, a behavior consistent with the increased TKE near the nozzle exit observed in the PIV data.

While the acoustic data at the 90° microphone location showed significant differences in the noise produced by each wedge, data at the 150° observer location showed that all three wedges are very similar to each other on both the thickened and thinned fan stream sides. The BPR8-W1 wedge does have the penalty of a bit more noise at peak frequencies on the thinned side but has less noise at higher frequencies than the other two wedges. The OASPL directivity data also has the BPR8-W1 wedge performing the

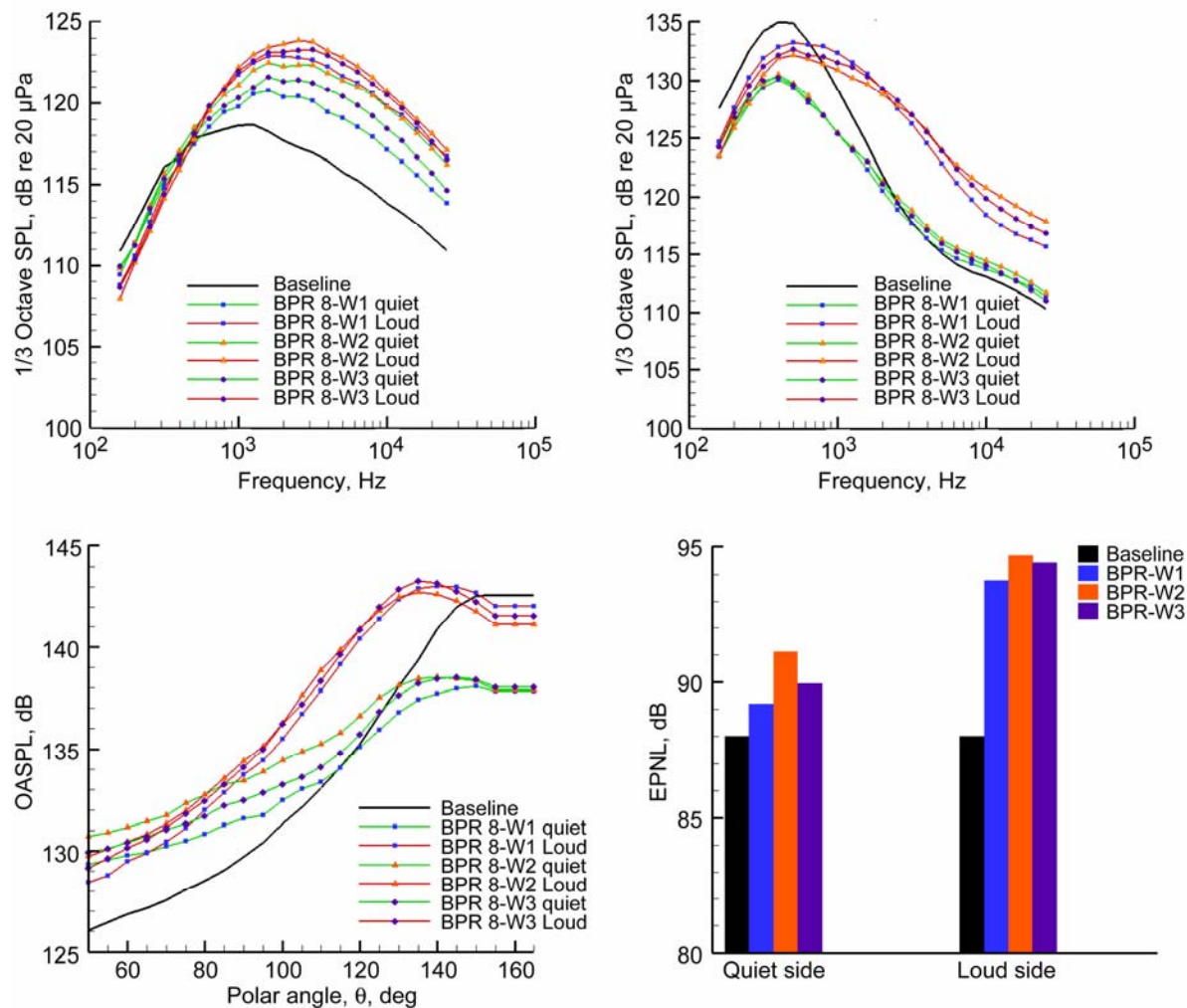


Figure 11.—Spectra from 90° (top left) and 150° (top right) with OASPL directivity (bottom left) and EPNL values (bottom right) for the BPR 8 wedge configurations at jet condition SP0050 (fig. 2). Note here that “Quiet” refers to the side of the jet with the enhanced fan stream and “Loud” refers to the side with the diminished fan stream. Also note that the OASPL values (bottom left) are identical after 155° because of the flight effect shear layer correction applied and, particularly, the extrapolation used to extend the data to the 165° location. EPNL values were calculated using a scale factor of 8 and a simulated flyover at Mach 0.28 and 1500 ft. Standard day atmospheric conditions were used for the acoustic propagation.

best. The penalties are lower than the other wedges at upstream angles and the cross over angle for noise reduction occurs around 115°, 10° lower than the BPR8-W2 wedge and 15° lower than the BPR8-W3 wedge. The directivity data supports the 150° spectral data showing that the acoustic benefits of the wedges are similar at the far downstream angles. Interestingly, the BPR8-W1 and BPR8-W2 wedges, which are the best and worst for noise levels respectively, have the same base length but different wedge angles. The BPR8-W3 wedge, on the other hand, which has the same wedge angle as the BPR8-W2 but a smaller base length, has data falling in the middle.

The far field data for a jet offset by a wedge in the fan stream showed some noise reduction on the thick fan stream side of the jet at downstream observer angles. But this noise reduction comes with the penalty of increased noise at higher frequencies than the baseline jet, at broadside and upstream angles. Additionally, each wedge design has a different “cross-over” angle where the wedge transitions from a

noise penalty to a noise benefit. To capture all these effects and make an overall comparison of each wedge, estimated perceived noise level (EPNL) values were calculated for each configuration. It should be noted, however, that EPNL is used only to compare the relative benefits or liabilities of each configuration and, because of the rig noise issues discussed in section II, not to show the expected noise for any one configuration in a full scale application. The EPNL results (fig. 11) show increase for all the wedges on both sides of the jet. In this metric, the noise reduction at downstream angles fails to overcome the increases in noise at broadside angles and higher frequencies when compared against the concentric baseline jet. The EPNL data also support the other data showing that the BPR8-W1 wedge performs the best acoustically while the BPR8-W2 performs the worst. With only three wedges tested, it is difficult to draw too many conclusions for future design, but, based on the flow and acoustic results, it is clear that all these wedge designs are too aggressive to achieve noise reduction at this engine bypass ratio.

2. Vanes

Many vane configurations were tested as part of the OST test program. Most of these vanes were built for the BPR 8 model system as part of a optimization experiment to determine the impact of different vane variables on noise and seek the combination that gives the lowest total noise (as determined by EPNL). The results of this study have been previously reported by Henderson et al. (ref. 9). This section, therefore, will focus on the acoustic results of the vane configurations to support the PIV data recorded and presented in section A. Data for the vane configurations tested at BPR 5 and at BPR 13 will also be examined in later section discussing the role of engine bypass ratio on the effectiveness of offset stream devices.

The vanes tested involved several design parameters. It is important to note that changes to any one parameter may also impact the choice of every other parameter in a positive or negative way. Figure 12 shows the acoustic spectra at the 90° and 150° observer locations, OASPL directivity, and EPNL for the BPR 8 vane configurations listed in table 1. First, the BPR8-V5 configuration, which was shown to be the most aggressive in terms of peak velocity decay and peak TKE, also produces the highest noise levels of all the vane configurations (though still has a small noise reduction relative to the baseline jet based on EPNL). The BPR8-V2 configuration, which has a peak velocity decay and peak TKE levels most similar to the baseline jet due to the low angle of attack and upstream vane position, shows some noise reduction compared to the baseline noise levels further making the case that the best acoustic results will come from more subtle changes to the flow. The best results, in terms of noise reduction, come from the BPR8-V4 configuration. Interestingly, this configuration has the same vane angle of attack as the BPR8-V5 configuration, which produced the highest noise levels, but the BPR8-V4 configuration moves one vane set further away from the nozzle exit while leaving the other fixed. The flow results show that this vane set has peak TKE levels similar to the BPR8-V2 case but with a more rapid peak velocity decay. This comparison begins to show the relationship between the axial location of the vane and the angle of attack. Another example of this relationship is shown by the BPR8-V2 and BPR8-V3 configurations. These vanes both have a vane angle of attack of 5°, half the angle of attack used by the BPR8-V4 and BPR8-V5 configurations, with the BPR8-V2 vanes set farther from the nozzle exit. In this case, moving the vanes closer to the nozzle exit reduces the total noise produced. In all cases, however, the amount of noise reduction (or increase), even on the side of the jet with the thickened fan flow, is relatively small.

3. S-Duct

The S-duct is perhaps the simplest offset stream concept considered during this test program. Simple in concept, however, does not necessarily translate into simple to construct and implement. Therefore, only one S-duct configuration was tested for each engine bypass ratio tested. Peak axial velocity decay and peak TKE decay for the BPR 8 S-duct configuration, presented in section A, showed that this S-duct is almost as aggressive as the wedges in shortening the jet plume and increasing the TKE. With the

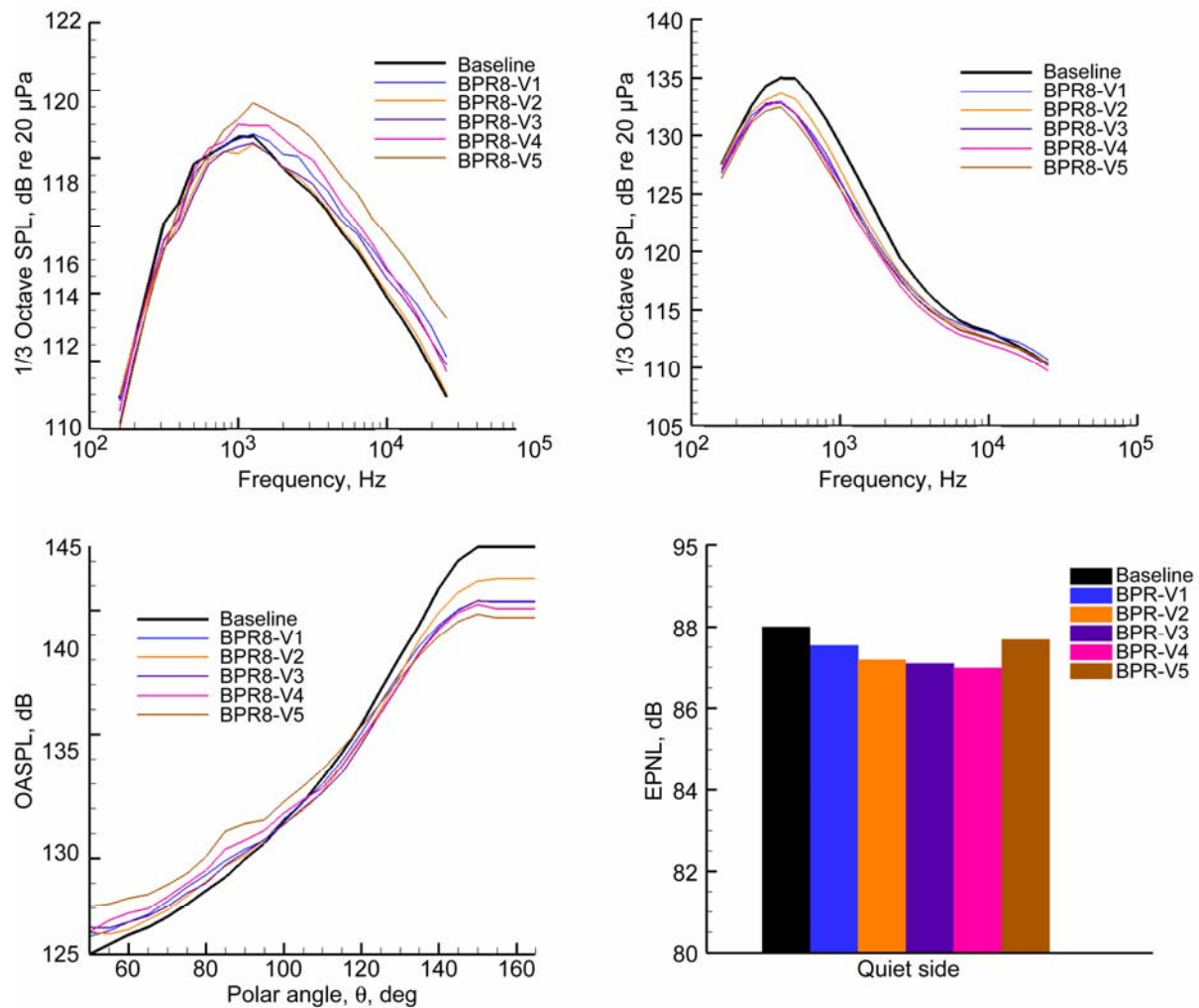


Figure 12.—Spectra from the BPR 8 vane configurations recorded at 90° (top left) and 150° (top right) relative to the jet axis shown with OASPL directivity (bottom left) and EPNL values (bottom right) for jet condition SP0050 (fig. 2). All data shown was recorded on the “quiet” side of the jet. The EPNL values were calculated using a simulated 1500 ft., Mach 0.28 flyover. Standard day atmospheric conditions were used for the acoustic propagation.

wedges, these changes led to significant increases in noise on both sides of the jet. The acoustic results from the BPR 8 S-duct offset jet, shown in figure 13, do not exactly follow this trend. Instead, installation of the S-duct results in directional noise reduction where noise levels on the thick fan stream side of the jet are reduced compared to the baseline concentric jet while noise levels are increased on the opposite side. As observed in the acoustic data from the vane configuration, the total noise reduction is small even on the side of the jet with the thickened fan flow. There is also a significant noise penalty on the opposite side of the jet. Unlike the vane configurations, however, it is important to note that only one S-duct configuration was tested so no additional reference point exists for adjusting the S-duct to create more or, likely, less offset for better noise reduction.

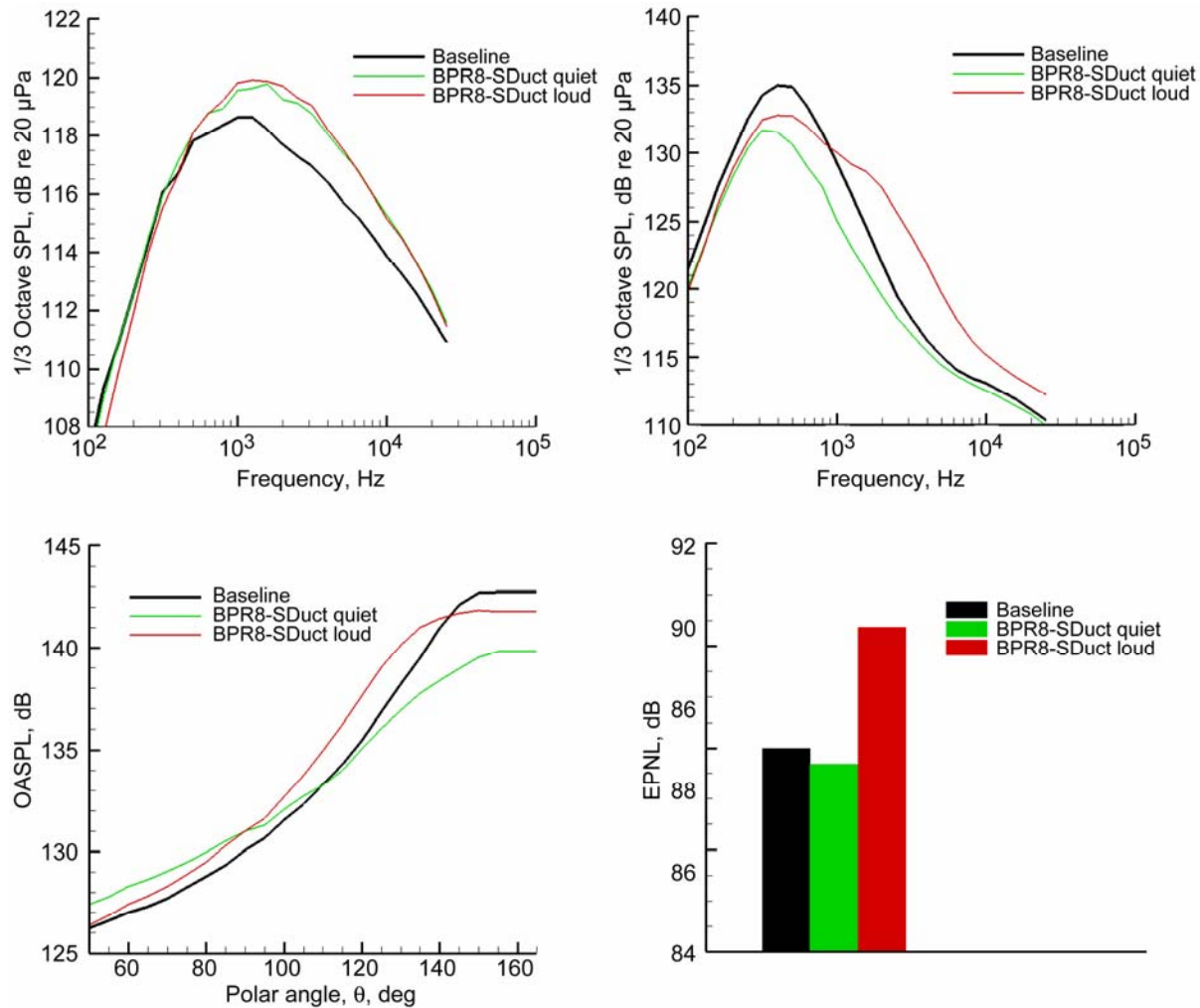


Figure 13.—Spectra for the BPR 8 S-duct configuration measured at the 90° (top left) and at 150° (top right) observer locations shown with OASPL directivity (bottom left) and EPNL (bottom right) at jet condition SP0050 (fig. 2). Both the thickened fan stream (“Quiet”) side and the thinned fan stream (“Loud”) side of the jet are shown. Although the noise penalty on the “Loud” side is significantly larger than the noise benefit on the “Quiet” side, this S-duct configuration shows the directional noise reduction envisioned with the implementation of an offset stream device.

4. Effect of Flight

The offset stream technologies were designed to create a thicker fan stream on one side of a separate flow jet to reduce the noise, though changes either in refraction or source strength. The flow data presented previously (section 4) showed that the TKE levels, at the fan stream to ambient shear layer, on the thickened side of the jet were similar to the baseline levels. On the side of the jet with the thin fan stream, however, there was a considerable increase in the TKE levels, particularly in the wedge and S-duct configurations where the core stream appears to directly interact with the ambient medium. The far field acoustic data measured with no flight effect (and shown in previous sections) showed noise reduction on the thickened fan stream side of the jet from the vane and S-duct configurations while data from the wedge cases all showed a significant increase in noise levels. Adding the effect of flight will weaken the jet to ambient shear layer, generally reducing the amount of noise produced by any jet. But does the noise reduction observed in the static case still hold when the effect of flight is added or do the offset stream technologies become more (or less) effective?

The effect of a flight stream on the noise reduction shown by the offset stream technologies must be considered. Figure 14 shows how the OASPL directivity and EPNL of the “best” wedge, vane, and S-duct configurations change when the effect of flight is added. Each plot shows the difference between the noise (evaluated as OASPL or EPNL) from the offset jet with or without the flight effect and the corresponding baseline jet with or without a flight stream. Negative values represent a noise reduction in this scenario. The results shown in figure 14 clearly illustrate that the added Mach 0.2 flight stream reduces the effectiveness of the offset stream technology deployed. The noise levels in the BPR8-W1 case, which created a noise increase in the static case, rose considerably when the flight stream was added. The noise reduction, based on EPNL, in the BPR8-V4 configuration was less with the flight effect although there appears to be only slight changes to the OASPL directivity. Noise data from the BPR8 S-duct without a flight stream showed a noise reduction on the thickened fan stream side of the jet. But the same configuration increases noise relative to the baseline with the flight effect. Far field noise data from each offset stream device shows that the offset stream jet is less effective at reducing noise when the effect of flight is considered.

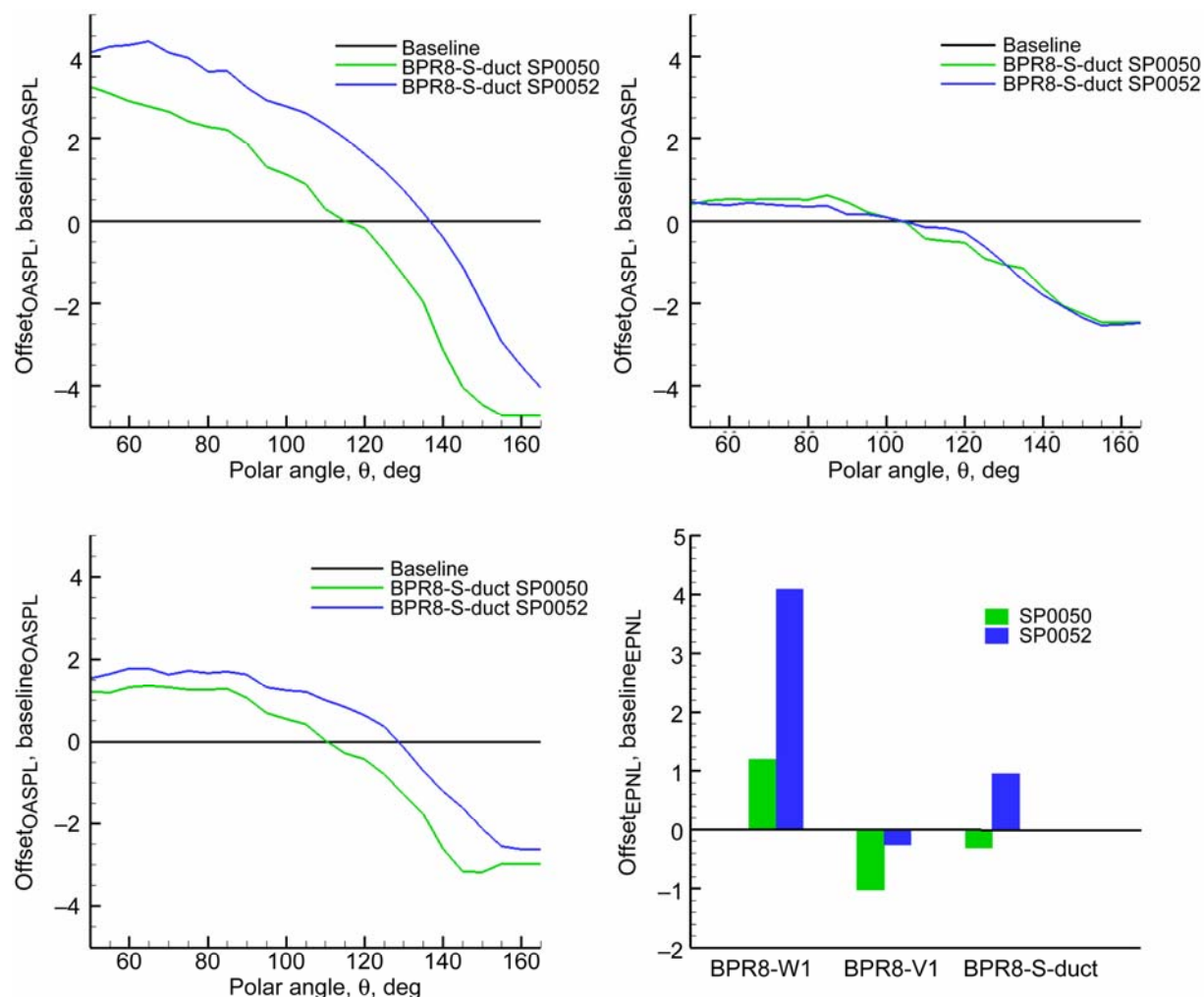


Figure 14.—The effect of flight on the OASPL directivity for the BPR8-W1 (top left), BPR8-V4 (top right), and BPR8 S-duct (bottom left). Also shown, the effect of flight on EPNL for each offset configuration (bottom right). Static jet condition SP0050 (green) and Mach 0.2 takeoff jet condition SP0052 (blue) were used. In each case the OASPL or EPNL for the baseline jet was subtracted from the OASPL or EPNL for the offset jet. Negative values, therefore, represent a noise reduction relative to the appropriate baseline jet. All data were recorded on the thickened fan stream side of the jet. EPNL values were calculated using a 1500 ft. level flyover at Mach 0.28 and standard day conditions.

5. Effect of Jet Condition

The offset stream jets were primarily intended to reduce jet noise during takeoff. However, each device will impact the noise (and performance) across the full engine operating range. Thus, if there is a noise penalty or significant thrust loss at a cruise condition for example, the next generation of offset stream devices may need to deploy only a specific engine operating conditions and stow out of the flow for the remainder of the flight. To investigate the impact of the offset stream devices at lower jet conditions, far field acoustic data near the cutback condition with a Mach 0.2 flight effect for the BPR 8 configuration (SP0032, fig. 2) will be examined. Also, the configurations studied at this jet conditions will be limited to the BPR8-W1 wedge, the BPR8-V4 vane, and the S-duct, the configurations that demonstrated the most noise reduction (or smallest noise increase) at the takeoff condition.

The effect of jet condition is presented in figure 15 which show the difference in OASPL directivity and EPNL between the baseline jet and the offset jet at a cutback jet condition (SP0032, fig. 2) and at a takeoff jet condition (SP0052, fig. 2). The wedge configuration (BPR8-W1) causes a large noise increase at the cut back jet condition consistent with the results shown at the takeoff (SP0052) condition. The jet

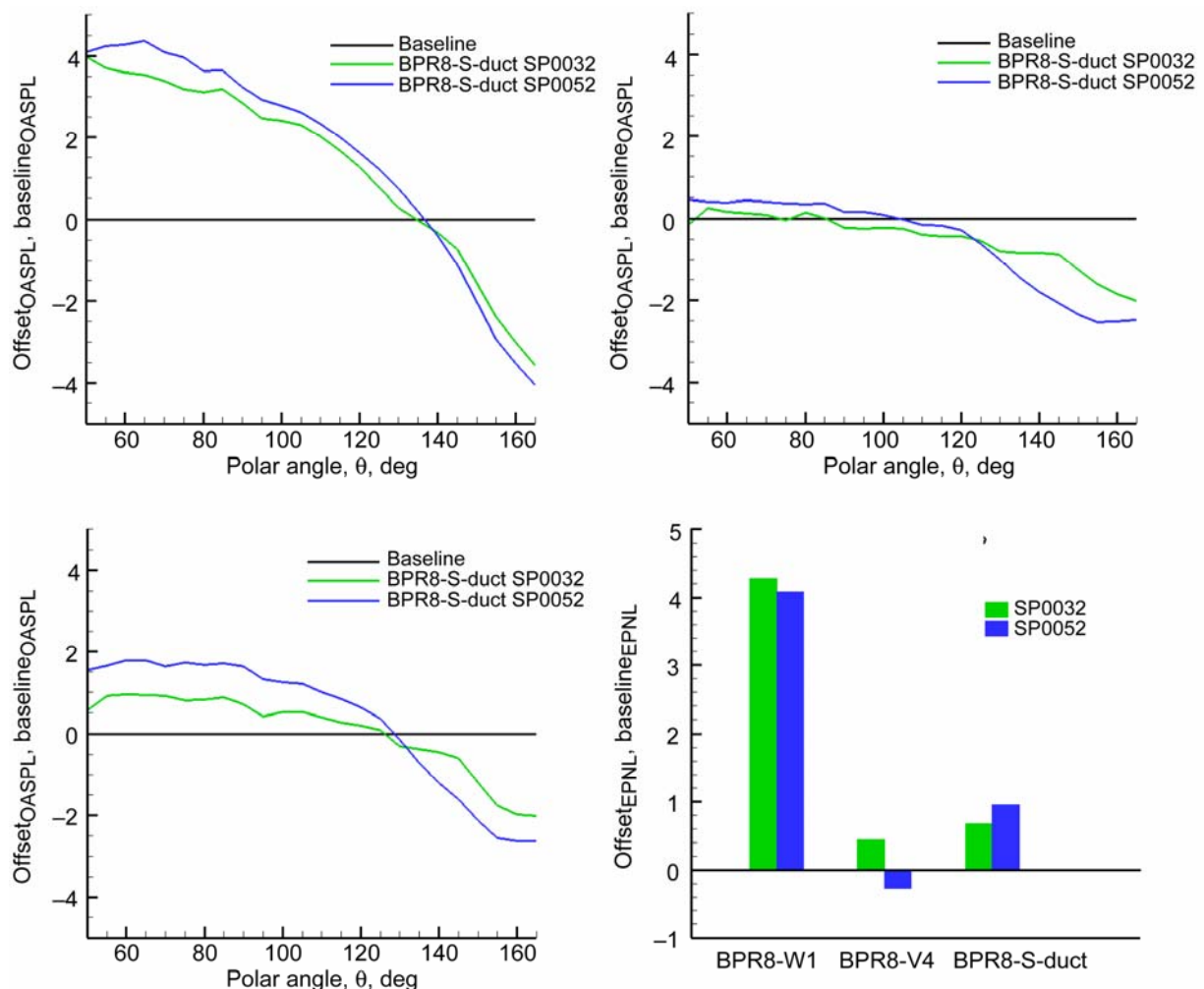


Figure 15.—Difference in OASPL directivity and EPNL between the baseline jet and the jet with the BPR8-W1 wedge (top left), the BPR8-V4 vanes (top right), and the BPR8 S-duct for jet conditions SP0032 and SP0052 (fig. 2). Negative values represent a noise reduction realized from the offset stream technology presented. All data shown were from the side of the jet with the thickened fan flow ("Quiet" side). EPNL was calculated using a 1500 ft. level flyover at Mach 0.28 and standard day conditions.

offset using the BPR8-V4 vanes, however, reduces the noise at the takeoff jet condition but increases the noise at the cut back jet condition even if the difference, based on EPNL, is small. The S-duct configuration behaves opposite of the BPR8-V4 case. The EPNL data shows that the jet offset using the S-duct creates less additional noise relative to the baseline at the cutback jet condition than at the higher takeoff jet condition. Again the difference is small. Overall the results are mixed between the offset stream devices being more or less effective at a lower jet condition. But in all cases the differences are small leading to the conclusion that the effectiveness of the offset devices tested is mostly independent of jet condition at this engine bypass ratio.

6. Effect of Engine Bypass Ratio

One goal of the Offset Stream Technologies test program was to investigate these devices at engine bypass ratios beyond those that could be tested at the smaller scale jet facilities. For comparison, tests were conducted using a wedge (BPR5-W1) at BPR 5 that matched critical parameters of a wedge tested at BPR 8 (BPR8-W1). Vanes using identical parameters were tested at bypass ratios 8 (BPR8-V4) and 13 (BPR13-V1). The S-duct configuration was tested at bypass ratios of 5, 8, and 13. While both time and hardware limited the configurations that were tested at all the bypass ratios, these points can be used to draw some preliminary conclusions on the effect of offset stream devices at higher bypass ratios. Figure 16 shows directivity and EPNL for the comparison configurations at each bypass ratio.

All the wedges tested at BPR 8 significantly increased the jet noise on both sides of the jet. The BPR8-W1 wedge generated the smallest noise increase. At bypass ratio 5, this wedge (BPR5-W1) exhibits very similar behavior. The OASPL directivity, compared to the appropriate baseline (fig. 16), shows an increase in noise at upstream angles and a decreased noise at downstream angles with a similar cross-over angle for both the BPR 5 and BPR 8 configurations. However, the wedge deployed in the BPR 5 jet shows a smaller noise increase than when installed in the BPR 8 configuration. This difference observed in the OASPL data is supported by the EPNL calculations that show the BPR8-W1 configuration is 2 EPNdB louder, relative to the BPR 8 baseline jet, than the BPR5-W1 configuration relative to the BPR 5 baseline jet. Because the BPR 5 configuration creates more noise in the core stream than the BPR 8 jet, some of the noise created by the wedge, and noticed in the BPR 8 data, may be masked at BPR 5. In either case, the wedges tested increased the far field noise so more data, preferably with a wedge that achieves some noise reduction, is needed before drawing any final conclusions on the wedge as a noise reduction concept in higher bypass ratio engines.

Unlike the wedges, the vanes did achieve some directional noise reduction without a flight effect. One set of vanes was tested at BPR 8 and BPR 13 to investigate the effect of vanes at higher bypass ratios. Ideally these vanes would also have been tested with the BPR 5 configuration but they were not compatible with that model. Figure 16 shows OASPL directivity and EPNL for the BPR 8 and BPR 13 vane configurations at a takeoff condition with a Mach 0.2 flight effect. At this jet condition, the both the BPR 8 and BPR 13 jets give approximately the same EPNL, slightly higher than the respective baseline jets. The OASPL directivity, however, shows that vanes at BPR 8 had more impact, relative to the BPR 13 jet, on the acoustics than the EPNL alone would indicate. At BPR 8, the OASPL measured with the vanes is increased at upstream angles and decreased at downstream angles relative to the baseline data. The OASPL directivity measured from the BPR 13 jet, offset with the vanes, is nearly identical to the BPR 13 baseline data. That the data from BPR 13 jet is largely unchanged by the vane is not entirely unexpected due to the amount of fan flow surrounding a relatively small core flow. Even if the core is offset, there is still plenty of fan flow surrounding the core to make the jet still appear very similar to the concentric jet. In the case of these vanes, the effect appears to diminish with the increase in bypass ratio.

The S-duct was the only configuration tested at all three bypass ratios and, therefore, is the best case to look at the effect of offsetting the fan and core streams at higher bypass ratios. Figure 16 shows the OASPL directivity and EPNL results for the S-duct, recorded at a takeoff condition with a Mach 0.2 flight speed, measured at BPR 5, 8, and 13. The directivity data shows that the S-duct deployed at the BPR 5 engine cycle has a significant noise penalty at upstream angles and a significant reduction at downstream angles.

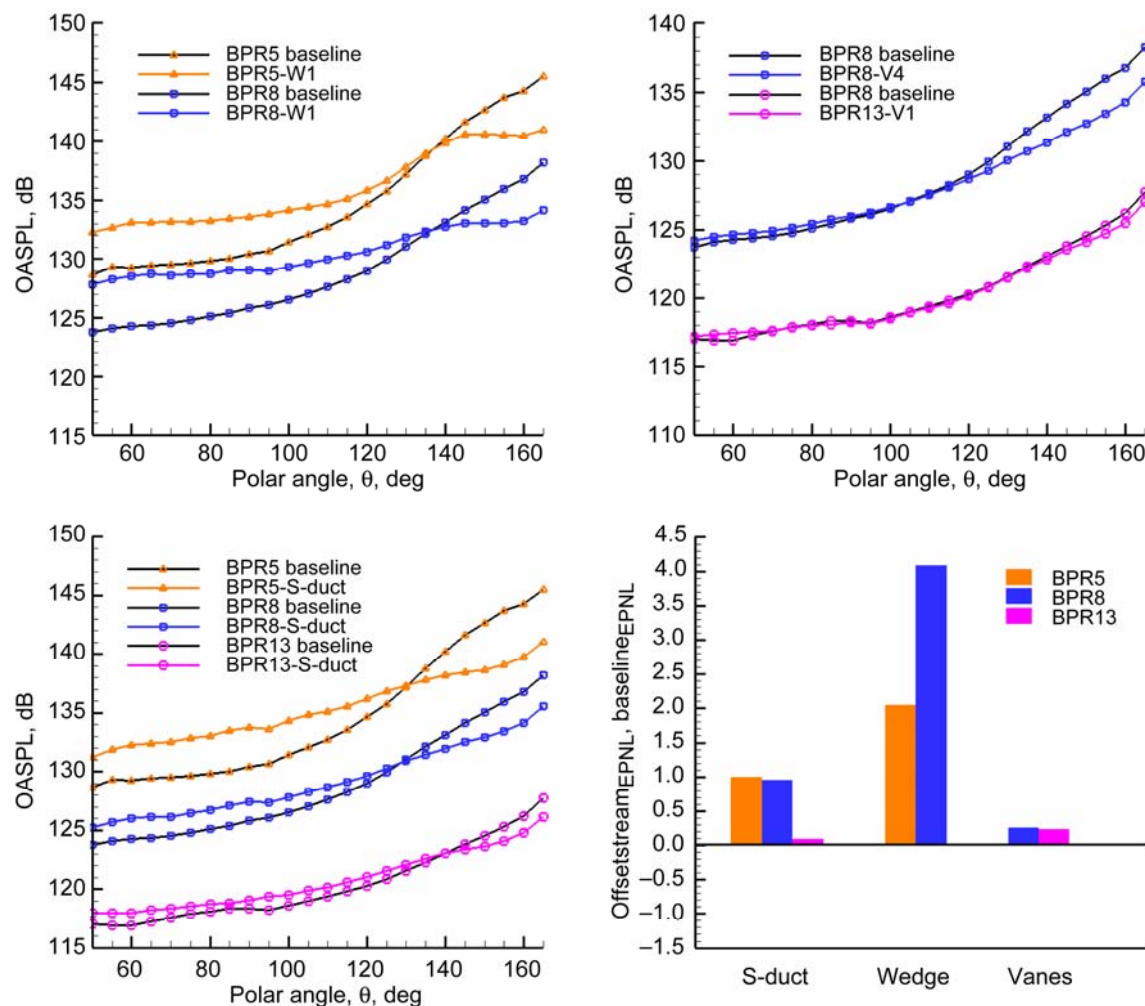


Figure 16.—OASPL directivity for the BPR5-W1 and BPR8-W1 configurations (top left), the BPR8-V4 and the BPR13-V1 vane configurations (top right), and the BPR 5, BPR 8, and BPR 13 S-duct configurations (bottom left) at a takeoff jet condition (SP0212, SP0052, and SP0712 for the BPR 5, 8, and 13 configurations respectively) with a Mach 0.2 flight effect. Also shown, the EPNL for each configuration as a difference from the baseline configuration. EPNL was calculated using a 1500 ft. level flyover at Mach 0.28 and standard day conditions.

This is consistent with all the configurations analyzed. The S-duct at BPR 8 shows the same trend but the absolute differences between the offset jet and baseline jet are reduced both in the upstream penalty and the downstream noise reduction. Finally, at BPR 13 there are only small differences between the directivity in the jet with the S-duct and the jet without the S-duct. This is reflected in the EPNL data from the offset BPR 13 jet which is nearly identical to the BPR 13 baseline. Interestingly, the EPNL data at the BPR 5 and BPR 8 engine cycles are very similar with the BPR 8 EPNL slightly lower. Apparently the upstream noise penalty, which was greater in the BPR 5 data, cancels with the downstream noise reduction, which was also greater in the BPR 5 data, when the data is integrated to calculate the EPNL. Thus, based on the S-duct data it appears that the acoustic effect of the offset jet diminishes as engine bypass ratio increases with the acoustic impact nearly disappearing at BPR 13. As stated earlier, this result is not unexpected since the increased fan flow at the higher bypass ratios naturally creates a significant shield on all sides of the jet without offsetting the two streams.

V. Conclusions

The concepts tested in the OST test were designed to modify the fan stream to azimuthally modify the noise propagated from the core and to reduce the jet noise produced on one side of a separate flow jet at the expense of increased noise on the opposite side. This directional noise reduction was to be achieved by either deflecting or rerouting the fan flow to create a thicker fan stream on one side of the jet. Three concepts, a wedge placed in the fan nozzle duct, a set of vanes in the fan duct mounted near the fan nozzle exit, and an S-duct to directly offset the fan stream from the core stream, were tested during the program. Flow measurements, recorded in the form of cross-stream stereo PIV, showed that each device achieved the desired fan stream to core stream offset. Additionally, the flow data showed that offset jets, particularly those using the wedge, generally had higher TKE near the nozzle exit and a more rapid decay of peak axial velocity when compared against the concentric baseline jet. This data complemented the far field acoustic data. The jets offset with the wedge devices, which had the greatest increase in TKE, also showed the largest increase in noise levels relative to the concentric baseline jet. The jet offset using the vanes achieved some noise reduction on the side of the jet with the thickened fan flow for several vane parameters. Ultimately, the vane configuration with the most noise reduction had very similar TKE and peak axial velocity decay as the baseline concentric jet. This result suggests that the optimal offset jet configuration will only make very subtle changes to the flow and that the wedges tested were overly aggressive. Far field data from the S-duct configuration also showed some directional noise reduction.

The initial acoustic results were all based on a takeoff jet condition with no flight effect. However, data were also acquired at the same takeoff jet condition but with a Mach 0.2 flight stream. The results, which were presented as deltas from a concentric jet with and without flight effect respectively, showed that the far field noise generated by each configuration generally trended towards the baseline configuration with flight. The wedge configuration did not increase the noise levels as much relative to the baseline with the flight. The data recorded from the jet offset by vanes still showed a noise reduction relative to the baseline jet but the amount of noise reduction was less. The jet offset using the S-duct, which showed a small reduction in noise relative to the baseline jet in the static case, had an increase in noise relative to the baseline jet when the flight effect was added. In each case, the effectiveness of the offset stream device was reduced when a flight stream was added.

Another series of tests were done to determine the effect of jet condition on the noise produced by the offset stream jets. Data were recorded at both takeoff and cutback conditions. The effectiveness of the offset stream device was then determined by again measuring the difference between the offset jet and the appropriate baseline jet. The results from these tests showed were mixed based on which offset stream technology (wedge, vane, or S-duct) was used. In each case, however, the differences were small leading to the conclusion that jet condition does not appear to play a strong role in the effectiveness of the offset stream devices tested.

Finally, the impact of offset stream technologies was measured for three different engine bypass ratios. The data for this section was sparse because of the limited number of devices that could be mounted on the models for all of the bypass ratios tested (BPR 5, 8, 13). Far field data was recorded from only one wedge at BPR 5 and BPR 8. Interestingly, the BPR 8 offset jet made more noise, relative to its baseline, than the BPR 5 offset jet produced relative to its concentric baseline. The cause of the increased noise at the higher bypass ratio is not known but it was speculated that the additional core noise from the BPR 5 jet masked some of the noise made by the wedge itself. For the vane device, data for one vane configuration was measured at BPR 8 and at BPR 13. Although there was little difference in the EPNL data for each configuration relative to its baseline jet, the OASPL directivity measured from each jet show the vanes have more impact on the noise at the lower bypass ratio. Similarly, acoustic data from the S-duct configuration, which was the only configuration that could be tested at all three bypass ratios, showed that the acoustic impact, particularly on the directivity, decreased as bypass ratio increased. Therefore, leaving out the wedge which was already shown to be over aggressive, it was concluded that the effect of offsetting the core and fan stream for direction noise reduction diminishes as bypass ratio increases. This result should not be unexpected because the amount of fan flow at the higher bypass ratios

allows for appreciable fan flow on all sides of a considerably smaller core flow. The current results, together with earlier results from other investigators suggest that the offset technology is promising for lower bypass ratio jets, the reduction provided being significantly reduced with increasing bypass ratio. Finally, the vane concept was tested at several jet conditions and multiple engine bypass ratios during the OST test program. The advantage of offsetting the core and fan stream reduces with flight so future designs may need to deploy only at low speeds, such as takeoff and landing, and retract the devices to minimize losses during cruise. Together these results show that offset stream technologies have a future for noise control in certain engine applications.

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14. ABSTRACT The concepts studied during Offset Stream Technology (OST) test were all designed to produce directional jet noise reduction in a separate flow engine configuration by redirecting the fan stream relative to the core stream, creating a thicker fan flow on one side of the jet. Previous studies, conducted at bypass ratios of five or less showed that lower noise levels would result on the thickened side. The OST test, conducted using nozzles with bypass ratios 5, 8, and 13, included flow and acoustic measurements over a wide range of engine bypass ratios, jet conditions, and flight speeds for three offset stream concepts: wedges, vanes, and an S-duct. Mean axial velocity data, measured in cross-stream planes showed that all these concepts successfully created the fan stream offset as intended. Additionally, far field acoustic measurements showed that the vanes and S-duct reduced the noise on the side of the jet with the thicker fan stream below the levels measured from the concentric baseline jet. However, adding a flight stream, to simulate Mach 0.2 forward flight, diminished the effectiveness of offset stream devices, reducing or completely eliminating most of the noise benefits. Furthermore, while engine condition (i.e., takeoff and cutback) did not have a large impact on the noise, engine bypass ratio had a significant impact on the effectiveness of the offset stream concepts. The offset stream devices had much less impact on the jet noise at higher bypass ratios than in lower bypass ratio configurations. In fact, only modest reductions were noted from the best bypass ratio 8 configuration. Above bypass ratio 8, the results from the offset jet were very similar to the baseline. Future work should, therefore, be directed at lower bypass ratio applications.					
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